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Responses of soil C stock and soil C loss to land restoration in Ili River Valley, China

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ABSTRACT

In the past decades, massive destroying of natural vegetation and extension of agricultural lands strongly affected soil carbon (C) cycling. Returning cropland to forestry or grass land is one of restoration measures sponsored by the Chinese government. Land use change exerts a great influence on soil microclimate and litter quality, and is therefore an important determinant of soil C dynamics. However, knowledge on the effects of land restoration on soil C in northwest China was limited. To address this problem, a study was undertaken in the arid Ili River Valley to estimate soil C dynamics for representative land uses: grassland and forest plantations (transformed from croplands), and cropland. The results showed that there were significant differences in soil C stock among the vegetation types. Soil C stock increased in poplar plantation eight years after conversion from cropland, whereas it significantly declined after conversion to spruce plantation. The 15-year-old poplar plantation had the highest soil C stock (59.60 Mg C ha^{-1}), including C sequestration in forest floor and in mineral soil (0–30 cm). High litter mass in the old poplar forest facilitated the accumulation of soil C. There were significant differences in soil respiration rate and cumulative soil C loss among the land use types, with the highest in clover grassland. Furthermore, the grassland had a higher Q_{10} value, which implies that an increase in soil temperature would lead to more soil C loss under global warming. Our results suggested that conversion of croplands to fast-growing woody crops might be beneficial to soil C sequestration, which was helpful for land management and mitigation of climate change.

1. Introduction

Soil is the largest carbon (C) reservoir in the terrestrial biosphere, and even a minor change in soil C storage may result in a significant alteration in atmospheric CO_2 concentration (Lal, 2004). Previous studies have underpinned the role of soil as a C sink, the importance of soil organic C (SOC) in the global C cycle and the potential feedback to climate change (Drewnik et al., 2016; Guo and Gifford, 2002; Wang et al., 2014). Soil respiration (Rs) is the second largest C flux in the terrestrial ecosystem, estimated to reach 50–75 Pg C $year^{-1}$ globally, 10 times greater than C emission from fossil fuel combustion (Raich and Schlesinger, 1992). The huge discharge of C by Rs directly affects the SOC concentration, which controls the soil fertility and productivity (Sarzhanov et al., 2017). Understanding C dynamics helps to determine the role of soil as a bridge for the terrestrial C storage and potential global warming.

SOC stock is controlled by a balance between C input from litter-fall and output by soil C loss (Bashkin and Binkley, 1998). The input of C to soil is affected by litter production and the rate of biomass allocation, while the output is controlled by organic matter content, litter C/N ratio, soil temperature and soil moisture (Laganière et al., 2010; Yan et al., 2017). Particularly, soil C stock is strongly affected by land cover and land use patterns which is changing rapidly due to human activities (Murty et al., 2002; Paul et al., 2003; Wasak and Drewnik, 2015). In the past decades, massive destroying of natural vegetation and extension of agricultural lands leaded to enormous soil C release. It was reported that net C efflux derived from land use change accounted for up to 12.5% of anthropogenic C emissions from 1990 to 2010 (Houghton et al., 2012). Wu et al. (2003) estimated that about 7.1 Pg SOC had been lost as a result of land use change in China, and most of the loss

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occurred in cultivated soils. Furthermore, previous studies have demonstrated that land use type is an important determinant of Rs by influencing soil microclimate, root growth, and quality of detritus (Jenkins and Adams, 2011; Wang et al., 2013). Thus, different ecosystems may exhibit different temperature sensitivities of Rs, commonly referred to as Q_{10} values (the factor by which Rs increases with a 10 °C rise in temperature) (Jenkins and Adams, 2011).

Returning farmlands to forestry or grass lands was one of restoration measures put into practice by the Chinese Government, which was so called as 'Grain-for-Green Program' (Deng et al., 2014). Afforestation of croplands may potentially reverse the process of soil C loss and increase ecosystem C storage (Arevalo et al., 2011; Yan et al., 2017). For example, several studies have found that afforestation increased SOC (Laganière et al., 2010; Murty et al., 2002). Nevertheless, the change in SOC may vary significantly according to forest type and cultivation stage (Wang et al., 2013). Conversion of cropland to grassland is one of the most effective strategies for C sequestration (Guo and Gifford, 2002; Machmuller et al., 2015). Therefore, quantifying the effects of land restoration on soil C dynamics is important to curb C loss from soils.

Due to low productivity of arid and semi-arid lands, soil C dynamics in these environments have received considerably less attention than other ecosystems (Conant et al., 2004; Maestre et al., 2013). However, arid lands cover a large portion of the Earth's land surface and store more than 25% of the global terrestrial C (Maestre et al., 2013). The predicted increases in temperature and changes in rainfall patterns in the dry-lands make ecosystem functions such as C cycling particularly sensitive to global change. In arid northwest China, excessive cultivation and grazing had resulted in severe land degradation, which was required to restore to grass land or forest plantation by the local government (Ait et al., 2009; Deng et al., 2014; Ren et al., 2018). However, little was known about the effect of land use conversion on soil C dynamics, detailed information was needed.

In this study, we conducted a field investigation for representative land use types in Ili River Valley, including cropland and grassland, poplar plantation and spruce plantation (converted from croplands). We hypothesized that land use change greatly affected soil C dynamics. The objectives of this study were: (1) to quantify and compare soil C stock in different land use types; and (2) to quantify the main factors impacting soil C stock and Rs.

2. Material and methods

2.1. Study site

Ili River Valley (80°09′–84°56′E, 42°14′–44°50′N) is located in the western part of the Tianshan Mountains in Xinjiang, northwest China. It is an inland continental river valley which surrounded on three sides by mountains. The region has a temperate continental climate with a mean annual precipitation ranging from 200 mm to 800 mm. The average annual temperature and evaporation range from 2.9 to 9.1 °C and 1260 to 1900 mm, respectively. The frost-free period lasts approximately 130–180 days, and the annual sunshine duration reaches 2700–3000 h (Ait et al., 2009). The soil type is Calciustoll (USDA Soil Taxonomy) originating from parent material of Loess sediments.

In Ili River Valley, massive grazing of natural pastures and extensive cultivation of farmlands had leaded to soil degradation (Ait et al., 2009). As an example, the grassland area decreased by 13.5% during 1985–2005, whereas the area of cropland increased by 10.1%. Major land uses include croplands (0.87 million ha), forest lands (0.62 million ha) and grasslands (3.2 million ha) in the Ili River Valley (Ait et al., 2009). Due to China's 'Grain-for-Green Program', croplands required to be returned to the green were mostly located in western region of Ili Valley where land cover had been strongly influenced by human activities.

The study site was located in the central region of western Ili Valley (Fig. 1). Soil texture is sandy loam with an organic carbon concentration of 7.3–14.6 g kg^{-1}, total nitrogen of 1.1–2.3 g kg^{-1} and a pH of 8–8.5 in the A horizon (Institute of Botany, Chinese Academy of Sciences, 1978). The study site was relatively flat with slopes $< 10°$ and the mean elevation reached 600 m. Groundwater was typically 2.0–2.3 m below the soil surface. Because natural precipitation hardly meets the water demand of plant development, irrigation was necessary. Water resources in this area originated from the Ili River, which gave an advantage to vegetation development. Poplar (*Populus* ssp.) and spruce (*Picea obovata*) plantations were established on farmlands in 1990s, formerly growing wheat (*Triticum aestivum*) or maize (*Zea mays*). Forest plantations had undergone intensive managements, such as irrigation, fertilization and weed control. Because of weed control management, herbaceous vegetation of the plantations such as steppe sedge, Japanese bromrgrass, and lovelyachnatherum were very sparse. As a typical species of legume forage, clover (*Trifolium repens*) was frequently used in the conversion of croplands to pastures, and harvested for silage 2–3 times a year.

2.2. Soil and litter sampling

We selected 15 sampling plots in central region of western Ili Valley, with three replications for each land use type including 8-year-old poplar plantation (YP), 15-year-old poplar plantation (OP), 15-year-old spruce plantation (SP), white clover grassland (WG), and cropland growing wheat (CL). The grassland and forest plantations were transformed from croplands. Characteristics of the land use types are given in Table 1. The plots were 25 m × 30 m for forests and 3 m × 3 m for grass and crop. During the growth season (from May to September) in 2007, plots in poplar plantations were irrigated once a month, with a rough water amount of 40–45 mm, whereas other plots were irrigated three times, with a rough water amount of 20–30 mm.

Soil samples were taken to a 30 cm-depth (for assessing C stocks according to the IPCC guidelines) (IPCC, 2003) using a soil auger, and separated into increments of 0–10, 10–20 and 20–30 cm depths. In July and August 2007, soil cores were collected randomly from 6 points in an "S" shape at each plot and were mixed to a composite sample by depth. A total of 45 soil samples were collected. In October 2007, forest floor litter samples were collected from three random subplots of 20 cm × 20 cm in each plot using a wooden frame. Litter samples were sorted into foliar (leaves and needles) and non-foliar materials (twigs and small branches), and then oven-dried at 80 °C to constant weights. All litter samples within each plot were pooled to one sample for chemical analysis.

Total C content was analyzed using Walkley-Black wet oxidation method (Allison, 1975), and total N was measured by Kjeldahl method (Bremner, 1996). A soil water mixture (1:2.5 for soil to water ratio) and a glass electrode were used to determine soil pH. Soil bulk density of the three depths was estimated using a steel core (100 cm^3 in volume), with soil fraction (> 2 mm) neglected.

2.3. Measurements of Rs and environmental factors

To quantify soil C loss in the land use types converted from croplands, 3–6 subsamples (soil collars) were distributed randomly in each plot of poplar plantation, spruce plantation, and clover grassland. In May 2007, PVC collars were inserted 2–3 cm from ground surface into the soil after removing litter and cutting off herbaceous layers (Conant et al., 2004). Collar heights were checked monthly to avoid possible changes in collar volume. Rs rate was measured with a Li-6400 portable CO_2 infrared gas analyzer (IRGA) equipped with a Li-6400-09 chamber (Li-Cor Inc., Lincoln, USA). During the growing season in 2007 (from May to September), Rs was measured 3 times in each plot between 10:00–14:00 per month (Conant et al., 2004).

Soil temperature was monitored simultaneously with Rs measurement using a constantan thermocouple penetration probe (Li6000–09 TC, Li-Cor Inc), inserted to a depth of 5 cm in the vicinity of collars. Soil

Fig. 1. Location of the study site.

samples at 0–10 cm depth were collected near the collars and oven-dried to constant weights to determine soil water content.

2.4. Cumulative soil C loss and soil C stock

Cumulative soil C efflux during the growing season (from 1 May to 30 September, 2007) was calculated by interpolating Rs rates between sampling days, and computing the sum of products of an average Rs and a time duration between the two consecutive measurements (Zhang et al., 2013). The equation was as follows:

$$M = 0.273 \times \sum \left[\frac{Rs_{i+1} + Rs_i}{2} \right] \times (t_{i+1} - t_i) \times 3600 \times 24 \times 44 \times 10^{-8} \quad (1)$$

where M represents accumulative C loss (Mg C ha^{-1}), i is serial number of sampling, and t is sampling time based on the Julian day (d).

Total soil C stock included C stock in mineral soil and in forest floor. Mineral soil C stock at 0–30 cm depth was calculated by multiplying soil C content by bulk density and by depth of soil layer (Bashkin and Binkley, 1998). Forest floor C stock was calculated by multiplying C

Table 1
Characteristics of main land use types in western Ili River Valley. The data are mean ± SE.

Parameters	Land use type[a]				
	WG	YP	OP	SP	CL
Plot latitude[b]	43°52′21.49″	43°51′54.12″	43°51′56.25″	43°51′58.91″	43°52′11.11″
Longitude	81°13′49.17″	81°14′7.67″	81°14′39.74″	81°12′45.97″	81°14′29.30″
Mean height (m)	0.55 ± 0.1	17.3 ± 0.7	20.7 ± 0.5	4.36 ± 0.3	0.52 ± 0.2
Tree diameter at breast height (cm)	None	19.2 ± 1.5	24.3 ± 1.8	5.18 ± 0.8	None
Soil C content (g kg^{-1})[c]	16.39 ± 0.16a	14.52 ± 0.15b	15.18 ± 0.10a	11.97 ± 0.12c	14.76 ± 0.12b
Soil N content (g kg^{-1})[c]	1.31 ± 0.05a	1.27 ± 0.03bc	1.44 ± 0.02a	1.25 ± 0.03c	1.25 ± 0.06c
Soil bulk density (g cm^{-3})[c]	1.21 ± 0.03b	1.24 ± 0.04a	1.23 ± 0.03ab	1.26 ± 0.07a	1.20 ± 0.03b
Soil pH[c]	8.30 ± 0.04ab	8.33 ± 0.03ab	8.36 ± 0.02a	8.27 ± 0.02b	8.37 ± 0.03a
Forest floor litter mass (Mg ha^{-1})[c]	None	5.1 ± 0.29b	8.2 ± 0.36a	2.1 ± 0.22c	None

[a] WG is an abbreviation for grassland; YP for young poplar plantation; OP for old poplar plantation; SP for spruce plantation; CL for cropland.
[b] Plot location represents a center of three plots for each vegetation type.
[c] Data followed by different lower case letters within the same row are significantly different at $P < 0.05$; Soil data are averages of 0–30 cm depth ($n = 3$).

content by forest floor mass. Considering that the plantations and grassland were established on previous croplands, soil C stock in the cropland served as a baseline.

2.5. Statistical analysis

All data were analyzed using SPSS 15.0 package (SPSS, Chicago, IL). An analysis of variance (ANOVA) was performed using general linear model (GLM) procedure to examine land use type effect. An exponential model was used to fit the relationship between Rs and soil temperature. Pearson correlation was carried out to examine the relationships between Rs and other variables. Significant difference for the statistical test was evaluated at $\alpha = 0.05$.

Exponential model:

$$Rs = ae^{bT} \tag{2}$$

Temperature sensitivity of Rs:

$$Q_{10} = e^{10b} \tag{3}$$

Where *a, b* are fitted parameters, *T* is soil temperature at a depth of 5 cm.

3. Results

3.1. Soil C stock in different land use types

There were significant differences in mineral soil C stock (0–30 cm depth) among the vegetation types ($P < 0.01$), with the highest (58.90 Mg C ha^{-1}) in WG and the lowest (44.53 Mg C ha^{-1}) in SP (Fig. 2). However, forest floor of OP sequestered an amount of 3.69 Mg C ha^{-1}, so total soil C stock in OP reached 59.60 Mg C ha^{-1}. Compared to the cropland (53.17 Mg C ha^{-1}), average rate of C sequestration of OP was 0.43 Mg ha^{-1} year^{-1} following afforestation.

Within 0–30 cm layer, soil C stock decreased with soil depth (Fig. 2). Foliar litter C/N ratio was 55.5, 41.1, 35.9 and 14.5 for SP, OP, YP and WG, respectively. There were significant differences in soil C content ($P < 0.01$) and foliar litter C/N ratio ($P < 0.001$) among the land use types (Table 2).

3.2. Rs in different land use types

During the growing season, Rs all showed distinct seasonal variations (Fig. 3). Rs rate in grassland reached the maximum in June, a month earlier than those in forests. There were significant differences in mean Rs among the vegetation types ($P < 0.01$), with the highest (5.39 μmol m^{-2} s^{-1}) in WG and the lowest (4.40 μmol m^{-2} s^{-1}) in SP (Table 2). Cumulative soil C loss by Rs during the whole growing season followed an increasing order as: SP < OP < YP < WG (Table 2). The soil C loss in WG was significantly higher than other ecosystem types ($P < 0.01$).

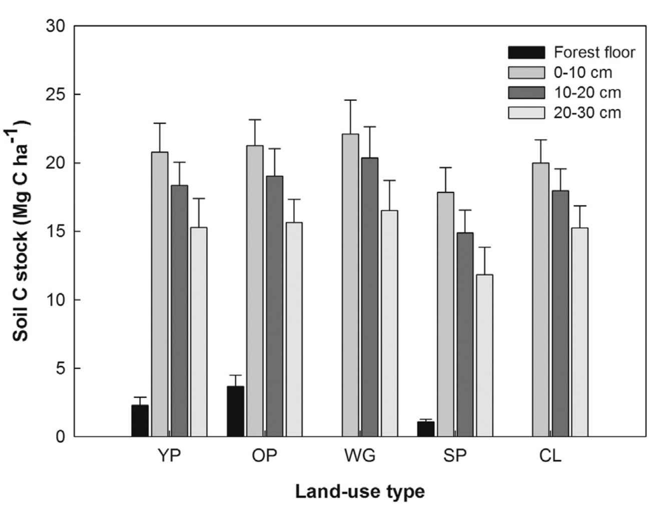

Fig. 2. Soil C stock of main land use types in western Ili River Valley. Vertical bars indicate standard error of means ($n = 3$). WG is an abbreviation for grassland; YP for young poplar plantation; OP for old poplar plantation; SP for spruce plantation; CL for cropland.

3.3. Soil environments in different land use types

During the growing season, soil temperature in WG increased quickly, and was significantly higher than those of plantations. There was a significant vegetation type effect ($P < 0.05$) on soil temperature. An exponential model explained the dependence of Rs on soil temperature, with R^2 ranging from 0.79 to 0.86 (Table 2; Fig. 4). Apparent temperature sensitivity (Q_{10}) of Rs followed an increasing order as: YP (1.54) < SP (1.68) < OP (1.86) < WG (2.13) (Table 2).

Average value of soil water content during the growing season was 26.2%, 25.1%, 23.3% and 18.6% for WG, YP, OP and SP, respectively. Pearson correlation revealed that soil water content was positively related to Rs across all land use types ($R^2 = 0.44$, $P = 0.023$) (Fig. 5). Pearson correlation revealed that Rs was highly related with foliar litter C/N ratio ($R^2 = 0.76$, $P < 0.001$) (Fig. 6).

4. Discussion

4.1. Variation in soil C stock with land use type

Soil C sequestration due to land use change is likely to be affected by multiple factors such as vegetation type, microclimatic condition, and managements, etc. (Deng et al., 2014; Laganière et al., 2010). In our study, soil C stocks increased after the conversion from croplands to young poplar forest (+3.52 Mg ha^{-1}) and to old poplar forest (+6.43 Mg ha^{-1}), whereas soil C stock significantly declined after the conversion to spruce plantation (−8.64 Mg ha^{-1}) (Fig. 2). Deng et al. (2014) have reported that vegetation type was the main factor affecting soil C stock change after land use conversion in China. Therefore, forest type posed great influences on soil C stock when climatic condition and managements were similar.

Vegetation type is a main factor determining quantity and quality of litter. Previous studies have indicated that grasslands have potentials to sequester more soil C (Gelaw et al., 2014). However, in our study, OP accumulated more soil C (59.60 Mg C ha^{-1}) than did clover grassland (58.90 Mg C ha^{-1}), because high decomposition rate of clover litter associated with low C/N ratio might result in small amount of C input into soil (Zhao et al., 2016). In contrast, litter mass in OP reached 3.69 Mg ha^{-1}, which was beneficial to soil C accumulation.

Many researchers have intensively studied variations in soil C stock result from afforestation on croplands (Laganière et al., 2010). At the national scale, Deng et al. (2014) reported a soil C sequestration rate (0–20 cm depth) of 0.33 Mg ha^{-1} year^{-1} following forest establishment on croplands in China. Estimated rates of mineral soil C sequestration of poplar plantations ranged from 0 Mg C ha^{-1} year^{-1} (Grigal and Berguson, 1998) to 1.6 Mg C ha^{-1} year^{-1} (Hansen, 1993). In our study, there was no significant difference in mineral soil C between poplar plantation and croplands, which indicated that it was not possible to observe measurable soil C variation during a decadal period. However, when forest floor C pool was included, the old poplar plantation showed a soil C sequestration rate of 0.43 Mg ha^{-1} year^{-1}. Since the wet oxidation method might lead to non-full combustion of organic carbon in litter samples, the C sequestration rate might be underestimated. Hence, afforestation of croplands with fast-growing poplar species has a potential to enhance soil C sequestration in the long term.

Table 2

Analysis on dependence of soil respiration on soil temperature in the land use types converted from croplands in western Ili River Valley[a]. The data are mean ± SE.

Land use type [b]	Cumulative soil C loss (Mg C ha^{-1})	Mean soil respiration rate (μmol m^{-2} s^{-1})	Exponential model	R^2	Q_{10}	Litter C/N ratio
WG	8.26 ± 0.45a	5.39 ± 0.35a	$Rs = 0.881e^{0.076T}$	0.86	2.13	14.5 ± 1.2d
YP	7.37 ± 0.37b	4.73 ± 0.29b	$Rs = 1.594e^{0.043T}$	0.81	1.54	35.9 ± 1.8c
OP	6.93 ± 0.35c	4.42 ± 0.25c	$Rs = 1.231e^{0.062T}$	0.79	1.86	41.1 ± 1.7b
SP	6.57 ± 0.31c	4.40 ± 0.28c	$Rs = 1.519e^{0.052T}$	0.79	1.68	55.5 ± 2.3a

[a] Data followed by different lower case letters within the same column are significantly different at $P < 0.05$; Soil respiration (Rs) and soil temperature (T) were averaged during the growing season ($n = 3$).

[b] WG is an abbreviation for grassland; YP for young poplar plantation; OP for old poplar plantation; SP for spruce plantation.

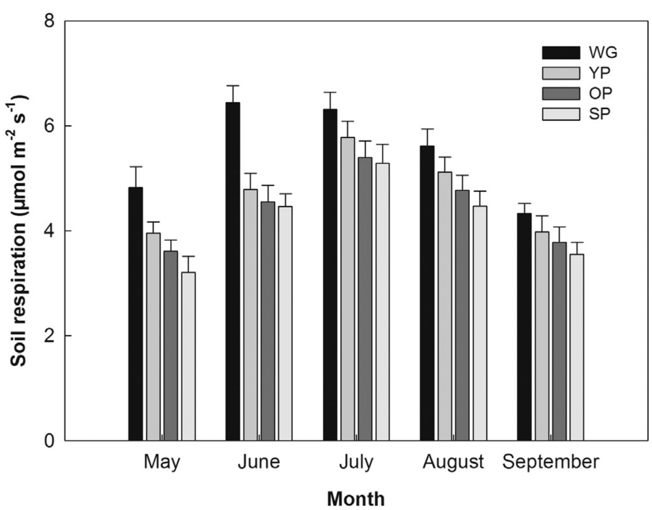

Fig. 3. Soil respiration of land use types transformed from croplands during growing period in western Ili River Valley. Vertical bars indicate standard error of means ($n = 3$). WG is an abbreviation for grassland; YP for young poplar plantation; OP for old poplar plantation; SP for spruce plantation.

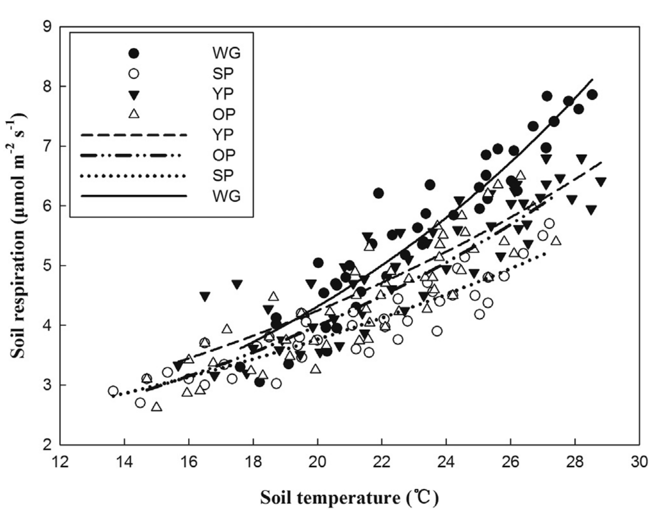

Fig. 4. Relationship between soil respiration and soil temperature for different land use types. Each point represents a mean per plot.

4.2. Variation in Rs with land use type

Growing evidences have demonstrated that vegetation type plays an important role in soil C release (Jenkins and Adams, 2011; Sarzhanov et al., 2017). In our study, soil temperature in grassland rose highly during summer, leading to an early increase in Rs (Fig. 4). On the contrary, soil temperatures in forests were consistently lower than in grassland due to a decreasing light intensity with canopy development. Moreover, soil water availability is an important factor influencing Rs

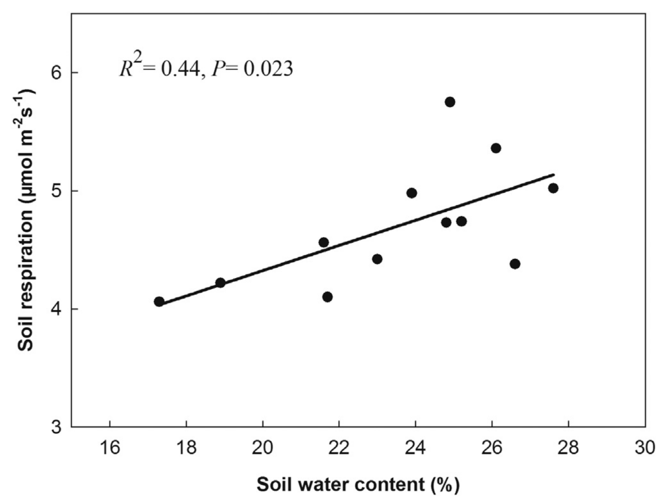

Fig. 5. Relationship between soil respiration and soil water content for different land use types. Each point represents a mean per plot.

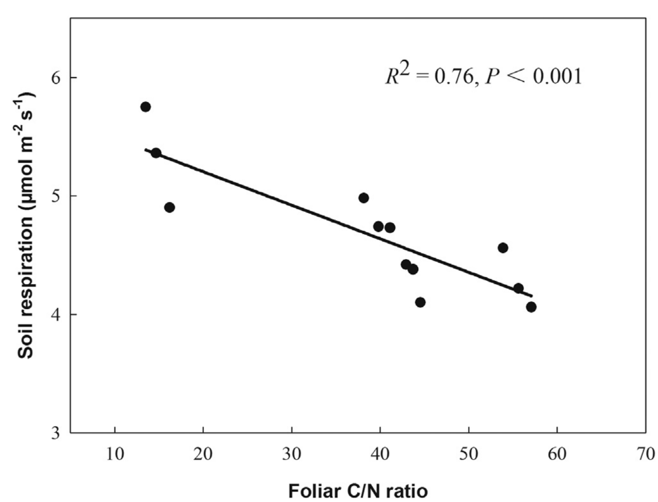

Fig. 6. Relationship between soil respiration and foliar litter C/N ratio for different land use types. Each point represents a mean per plot.

(Raich and Schlesinger, 1992; Zhang et al., 2013). In our study, soil water content differed among land use types, and high soil moisture in grassland was positively related to high Rs. Therefore, significant differences in Rs among land use types could be attributed primarily to plant-mediated effect on soil microclimate.

Previous studies have showed that Rs is consistently higher in grassland than that in forest under similar soil conditions (Raich and Schlesinger, 1992). In this study, cumulative soil C loss in grassland was significant higher than those of forest plantations. With no C allocation to wood production, grasses usually deliver more photosynthate to roots than trees do (Laungani and Knops, 2009). Furthermore, litter

chemical composition and decomposability varies significantly among vegetation types (Wang et al., 2013). Tewary et al. (1982) argued that Rs was closely related with N and lignin contents of litter in northern India. In our study, clover litter had the lowest C/N ratio (Table 2), which was partly responsible for its high Rs rate.

4.3. Q_{10} variation with land use type

Temperature sensitivity of Rs is an important parameter in predicting C emission associated with ongoing global warming (Curiel Yuste et al., 2004). Raich and Schlesinger (1992) found that Q_{10} values ranged from 1.3 to 3.3 across different land use types. In China, previous studies have indicated that different vegetation types exhibit different Q_{10} values, ranging from 1.52 to 3.05 (Zheng et al., 2009). In our study, there were significant differences in Q_{10} value among the land use types, in accordance with previous studies.

Vegetation type is a main factor controlling temperature sensitivity of soil respiration because of different phenological patterns of below-ground activities within different land use types (Curiel Yuste et al., 2004). In our study, clover was more sensitive to a rise in soil temperature than other plants during the growing season, leading to a higher Q_{10} value. Furthermore, plant litter is an important substrate for soil microbial metabolic activities, and thus influences the response of Rs to temperature. For different ecosystem types with similar climatic conditions, biological and chemical properties may be responsible for Q_{10} variations to a great extent.

5. Conclusion

In sum, our results showed that soil C stock increased in poplar plantation eight years after the conversion from cropland, whereas it significantly declined after the conversion to spruce plantation. High litter mass in the old poplar forest facilitated the accumulation of soil C. There were significant differences in Rs rate among the vegetation types, with the highest in clover grassland during the growing period. Furthermore, the clover grassland had a higher Q_{10} value, which implies that an increase in soil temperature would lead to more soil C loss in the future. Our results suggest that afforestation with fast-growing tree species such as poplar may enhance soil C sink, which is helpful for mitigation of climate change.

Acknowledgments

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